blooms contain algae that produce highly toxic biological toxins (such as microcystin, saxitoxin, and short-brown algal toxin, etc.). These toxins accumulate continuously through the food chain, polluting drinking water and seafood, poisoning humans, livestock, pets, and wild animals, and some can cause rapid onset while others accumulate slowly to affect health (Brenckman et al., 2025; Chang, 2025). In terms of economy, harmful algal blooms affect fishing, aquaculture, tourism, and recreational activities, causing annual losses of hundreds of millions of dollars and posing difficulties for the development of "blue economy" in many areas. In terms of water resources, harmful algal blooms make daily water quality testing and risk assessment more difficult, and some lakes and reservoirs cannot be used as drinking water sources normally, increasing the cost of water purification and treatment in water plants (Igwaran et al., 2024).

To address this issue, various management approaches have been adopted, mainly divided into three categories. The first is proactive prevention, such as reducing the inflow of nutrients into water bodies, managing water resources properly, and utilizing land rationally; the second is direct control within the water body, using methods from physics, chemistry, and biology; the third is relying on monitoring and early warning to reduce the harm caused by the rampant growth of algae (Igwaran et al., 2024). Remote sensing, molecular detection, and various sensors are increasingly used in monitoring, and new biological management ideas are gradually being implemented. However, the large-scale promotion of these technologies still faces obstacles and is restricted by policies, management, and social factors; in addition, the impact of climate change makes it even more difficult to predict the governance effects (Lan et al., 2024; Liu et al., 2025; Zahir et al., 2024).

This study will focuses on the control issues of harmful algal blooms in freshwater and marine environments, analyzing the advantages, disadvantages and applicable scenarios of various governance methods. This article integrates the latest global research, sorts out various measures such as source control, water treatment, and hazard mitigation, as well as ongoing research technologies. At the same time, it focuses on the comprehensive governance approach that integrates multiple disciplines and technologies, discusses future development directions, and explores how to establish a more complete monitoring, analysis and policy system to reduce the environmental and social losses caused by algal blooms.

2 Formation Mechanisms of Harmful Algal Blooms

2.1 Excessive nutrients lead to rampant growth of algae

Human activities have led to an increasing accumulation of nutrients in water bodies, which is a significant factor contributing to the rapid proliferation of harmful algae. Especially when the levels of nitrogen and phosphorus are too high, algae will grow in large quantities in various water bodies such as freshwater and estuaries. Nutrients from agricultural fertilization, discharged domestic sewage, surface runoff formed by urban rainfall, and airborne sediment, all of which may cause the continuous accumulation of nutrient salts in water, providing sufficient growth conditions for algae and eliminating the limitation of insufficient nutrients. Such environmental conditions are more favorable for fast-growing algae, such as cyanobacteria and some diatoms (Figure 1) (Brenckman et al., 2025). In studies conducted in many regions around the world, it has been found that the more nutrients there are in water bodies, the more frequently and on a larger scale harmful algae outbreaks occur, and the more significant the impact is. After the large-scale proliferation of algae, it often leads to oxygen deficiency in water bodies, produces odors and releases toxins, thereby damaging water quality and affecting the entire ecosystem. Studies on lakes, rivers, estuaries, and coastal waters have also shown that when the nutrient salt levels in water bodies increase, the number of planktonic organisms usually increases significantly. This further indicates that excessive nutrients are an important cause of algae outbreaks, and therefore, from the perspective of controlling nutrient input, this issue can theoretically be managed and alleviated.

In addition to excessive nutrients, the types and proportions of nutrients, as well as when they enter the water, are also crucial for the outbreak of algae. Many harmful cyanobacteria and flagellate algae have special abilities, such as being able to fix nitrogen from the air, storing excess nutrients, or efficiently utilizing certain forms of nitrogen. These abilities allow them to survive even in cases of nitrogen and phosphorus imbalance and unstable nutrient